



Wave Dispersion in Cylindrical Tubes: Applications to Hopkinson Pressure Bar Experimental Techniques

**by Libo Ren, Mike Larson, Bazle A. Gama, and
John W. Gillespie, Jr.**

ARL-CR-551

September 2004

prepared by

**Center for Composite Materials
University of Delaware
Newark, DE 19716**

under contract

DAAD19-01-2-0005

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) September 2004		2. REPORT TYPE Final		3. DATES COVERED (From - To) January 2003–April 2003	
4. TITLE AND SUBTITLE Wave Dispersion in Cylindrical Tubes: Applications to Hopkinson Pressure Bar Experimental Techniques			5a. CONTRACT NUMBER DAAD19-01-2-0005		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Libo Ren,* Mike Larson,* Bazle A. Gama,* and John W. Gillespie, Jr.*			5d. PROJECT NUMBER 622618.AH80		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Delaware Center for Composite Materials Newark, DE 19716			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRD-ARL-WM-MB Aberdeen Proving Ground, MD 21005-5069			10. SPONSOR/MONITOR'S ACRONYM(S) ARL-CR-551		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES *University of Delaware, Center for Composite Materials, Newark, DE 19716					
14. ABSTRACT It is well known that harmonic waves with higher frequencies travel slower than those with lower frequencies and that they are known as “wave dispersion” in finite diameter rods. From the frequency equation, the phase speed can be determined if the wavelength is known. A dispersion correction methodology uses the frequency equation to disperse a waveform to a specific location of interest. Dispersion correction methodologies are generally used in split-Hopkinson pressure bar (SHPB) techniques to reduce experimental data accurately. This report investigates wave propagation and wave dispersion in cylindrical tubes. Based on the work of Mirsky and Herrmann (M-H), the phase speed can be solved for wave motion along a cylindrical tube with a specific thickness-to-radius ratio. A numerical algorithm is developed to solve the M-H model and is compared with the solutions obtained from a three-dimensional finite element model. It is found that the first mode of the M-H solution gives the correct phase speed for wave motion in a tube. A modification to the traditional inverse fast Fourier transform algorithm is proposed for better prediction of the dispersed signal. The effects of the tube dimensions and the accuracy of dispersion correction in SHPB experiments are also discussed.					
15. SUBJECT TERMS wave dispersion, split-Hopkinson pressure bar experiment, cylindrical tubes					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 42	19a. NAME OF RESPONSIBLE PERSON Libo Ren
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (Include area code) 302-831-0248

Contents

List of Figures	iv
Acknowledgments	v
1. Introduction	1
2. Solution of M-H Model	3
3. Modification of Traditional Dispersion Algorithm	7
3.1 Solution of Phase Speed	7
3.2 Reconstruction of Waveform	7
4. Finite Element (FE) Analysis	9
5. Results and Discussion	11
6. Conclusions	16
7. References	17
Distribution List	19

List of Figures

Figure 1. Schematic diagram of SHPB setup.....	1
Figure 2. Solution of the frequency by 3-D theory and shell theory for various m values.....	5
Figure 3. Solution of the frequency equation by shell theory for various $m = h/R$	6
Figure 4. c_k / c_c when $\delta = h / \Lambda$ approaches infinity, $c_c = \sqrt{E / \rho}$	6
Figure 5. Explanation of new dispersion algorithm for SHPB.	8
Figure 6. FE model of a cylindrical tube.	10
Figure 7. Definition of stress wave applied on the end surface of the cylindrical tube.....	10
Figure 8. Strain vs. time at the mid-length of the tube.	11
Figure 9. Axial strain predicted by M-H model and FE analysis for the tube with $m = 0.548$	12
Figure 10. Axial strain predicted by M-H model and FE analysis for the tube with $m = 0.667$	13
Figure 11. Comparison of new and traditional dispersion algorithms.....	14
Figure 12. Dispersed wave in rod determined by the new algorithm and traditional algorithm. Material Poisson's ratio = 0.29.	14
Figure 13. Stress history of all elements at $z = 1.00$ m along $X = 0$ axis.	16

Acknowledgments

This report is prepared through participation in the Composite Materials Technology Collaborative Program sponsored by the U.S. Army Research Laboratory under Cooperative Agreement DAAD09-01-2-0005. Libo Ren would like to thank Dr. J. R. Xiao and Dr. Y. P. Duan at the University of Delaware-Center for Composite Materials for helpful discussions on wave propagation theory.

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1. Introduction

The split-Hopkinson pressure bar (SHPB) experimental technique has become a standard method in determining the dynamic mechanical properties of materials. The Hopkinson pressure bar technique was originally developed by B. Hopkinson (1) in 1914 to measure the pressure generated by the detonation of explosives. In 1948, R. M. Davies (2) conducted a critical study of the Hopkinson pressure bar technique. He developed the axial and radial strain measurement system and analyzed the wave dispersion effects. In 1949, H. Kolsky (3) invented the SHPB technique. In his work, he used the same system as Davies' to measure the strain. At the same time, he developed a one-dimensional (1-D) model to perform experimental data analysis. The work of Hopkinson, Davies, and Kolsky established the foundation for the development of the SHPB technique. Figure 1 shows a classic SHPB test setup, which consists of one striker bar (SB), one incident bar (IB) and one transmission bar (TB), equal in diameter and usually made from the same material. Strain gages are mounted on the surfaces of IB (SG1) and TB (SG2) to record the strain. The specimen (SP) is sandwiched between the IB and the TB. The SB, powered by pressured gas, will hit the IB. A compressive stress wave will travel along the IB and reach the IB-specimen (IB-S) interface. At this interface, one part of it will be reflected back into IB, and the rest will be transmitted to the TB through the specimen-transmission bar (S-TB) interface. The strain gage SG1 will record two waves: incident wave and reflected wave and the strain gage SG2 will record only the transmitted wave. Data reduction on these three waves will provide the stress-strain response of the specimen material under dynamic loading.

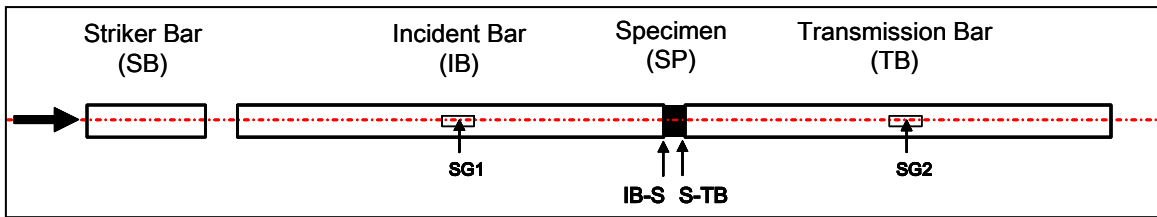


Figure 1. Schematic diagram of SHPB setup.

The classical SHPB data analysis is based on 1-D wave propagation theory in long rods. Several assumptions have been made for the 1-D theory. Two important assumptions are as follows: (1) stress wave propagation in the bars is 1-D, and (2) the bars are free of dispersion effects. Actually, these two assumptions are not satisfied for finite diameter bars. Based on such assumptions, the strain data measured at the middle point of the bars are directly used as the strain at the interfaces to reduce the data. Strictly speaking, wave propagation in cylindrical bars is three-dimensional (3-D) in nature: both axial and radial stresses, and strains are generated when the stress wave travel along the bar. Such variables are functions of radial dimension, so they are not uniform across the cross section. The wave dispersion effect exists, which means

that the harmonic wave with higher frequencies travels more slowly than the wave with lower frequencies. Due to this effect, the wave shape keeps changing as it travels along the axial direction. This effect should be considered for accurate data reduction.

Many authors have investigated the wave dispersion effect in order to modify the classical 1-D data analysis algorithm. Their study is based on the work of Pochhammer (4) and Chree (5), who independently solved the problem of wave propagation in an infinite cylindrical rod with finite diameter and derived the frequency equation. This frequency equation establishes the relationship between phase velocities and wavelengths of harmonic waves. Later Davies (2) and Bancroft (6) solved the equation numerically for some limiting cases. With the help of modern computers, the frequency equation can be easily solved over the complete range of geometric and material parameters. Follansbee and Frantz (7) and Gong et al. (8) investigated the effect of wave dispersion correction for the SHPB test and found that significant improvement on the stress-strain data can be achieved by wave dispersion correction. During dispersion correction, Fourier transformation (FT) is used to decompose the measured strain data into its harmonic waves. The dispersion correction methodology is then applied for each component frequencies. Finally, inverse FT is performed to get the dispersed wave at the IB-S and S-TB interfaces. Other dispersion correction methods were also suggested, e.g., in Li and Lambros (9). Currently wave dispersion correction has become a standard procedure in SHPB data analysis.

In this report, the wave dispersion in cylindrical tubes for the SHPB application is investigated. This study has become important and indispensable because recently cylindrical tubes have been used for SHPB experiments. For example, Dowling et al. (10) performed a dynamic punch shear test to study the mechanical properties of metals. This technique uses a transmission tube in place of the TB, such that the IB can shear a cylindrical disc through the specimen. This test method is still being extensively used today. Another example is determining the mechanical properties of low-strength, low-impedance materials under dynamic loading. If solid TBs are used for the SHPB test, the noise level is so high that proper interpretation of the transmission signal becomes impossible. To solve this problem, some researchers have used visco-elastic bars e.g., see Zhao et al. (11). The disadvantage of using visco-elastic bars is that additional assumptions have to be made about the visco-elastic material properties, which may not represent the true characteristics of the bar materials at high strain rates. Furthermore, the material properties are functions of temperature, moisture, and aging conditions, which are difficult to control. In addition, the dispersion correction algorithm now becomes very extensive and time consuming due to the visco-elastic nature of the bar materials. Other researchers have put forward the idea of using a hollow cylindrical tube for the transmission part of the SHPB test. Recently, Chen et al. (12) used IB and transmission tube made of high-strength Al alloy to measure the dynamic mechanical properties of silicon (Si) rubber materials. In this way, they obtained higher amplitude transmission signal that was achievable using a solid bar. The problem is that they did not perform any dispersion correction on the incident and transmission signals, which were collected from midpoints of the bar/tube. They used pulse shaper to filter

the high-frequency components in the waveform and then claimed that dispersion correction was not necessary. This argument is not correct because the same argument can be applied to the traditional SHPB test, which means if pulse shaper is used, dispersion correction is not necessary any longer. It is not clear how to define the lower limit of high-frequency wave components without a dispersion correction methodology. The use of a pulse shaper can improve the result but cannot eliminate the necessity of dispersion correction. It is still necessary to investigate the wave propagation in a cylindrical tube and find the appropriate dispersion relations, and is the objective of the present study.

Wave propagation in infinitely long tubes has been discussed by several authors, as early as in the 1920s. Ghosh (13) studied the longitudinal motions of a hollow cylinder with 3-D theory. In 1952, Fay (14) investigated this problem again and derived the frequency equation. But there was an error in his equation, which was pointed out by Herrmann and Mirsky (15). The work of Mirsky and Herrmann (M-H model) is considered the most comprehensive treatment (15, 16). They used both 3-D theory and shell theory to study the wave motion in cylindrical tube. Using 3-D theory, they derived the exact frequency equation, and their shell theory considered membrane effect, bending effect, transverse shear deformation, and rotary inertia. They claimed that the results of 3-D theory and shell theory were very close.

This study is based on the work of Mirsky and Herrmann (16). First, the two frequency equations will be solved again to make sure that the shell theory really gives a solution to phase speed, which is accurate enough. Then the results of M-H shell theory will be applied to the SHPB test. It will be shown that the first mode solution is correct for the SHPB application. A modified dispersion correction algorithm will be suggested to make accurate prediction of strain at the IB-S and at the specimen-transmission tube (S-TT) interfaces. Finally, the effects of the tube geometry on the accuracy of data reduction will be discussed.

2. Solution of M-H Model

As mentioned earlier, Herrmann and Mirsky (15, 16) derived the exact frequency equation for cylindrical tubes by solving the 3-D problem and one approximate frequency equation through shell theory. The 3-D theory gave the exact frequency equation in cylindrical coordinates (r, θ, z) (15):

$$\begin{aligned}
 F_{3D}(c, h/\Lambda) = & [K_{10}(\beta)K_{01}(\gamma) + K_{01}(\beta)K_{10}(\gamma) + (8/(\pi^2\beta\gamma ab)) \\
 & + FK_{11}(\gamma)K_{00}(\beta) + (1/F)K_{11}(\beta)K_{00}(\gamma)] + [(1 + \bar{B})^2/(F\gamma^2 ab)]K_{11}(\beta)K_{11}(\gamma) \\
 & - [(1 + \bar{B})/(\gamma ab)][aK_{11}(\gamma)K_{10}(\beta) + bK_{11}(\gamma)K_{01}(\beta)] \\
 & - [(1 + \bar{B})/(F\gamma ab)][aK_{11}(\beta)K_{10}(\gamma) + bK_{11}(\beta)K_{01}(\gamma)] = 0, \tag{1}
 \end{aligned}$$

where

$$K_{mn}(z) = J_m(zb)Y_n(za) - J_n(za)Y_m(zb), c_c = \sqrt{(\lambda + 2\mu)/\rho c_s} = \sqrt{\mu/\rho}$$

and

$$\beta^2 = \alpha^2 \left(\frac{c^2}{c_c^2} - 1 \right), \gamma^2 = \alpha^2 \left(\frac{c^2}{c_s^2} - 1 \right), \bar{B} = \left(\frac{c^2}{2c_s^2} - 1 \right), F = \frac{\alpha^2 \bar{B}^2}{\beta\gamma}. \quad (2)$$

In equation 2, α is the wave number $2\pi/\Lambda$ and J_m, Y_m are the Bessel functions, a and b are the inner and outer radii of the tube, λ and μ are Lamé's constants, ρ is tube material density.

c is the phase speed to be solved, $h = b - a$ is the thickness of the tube wall and Λ is the wave length. Mirsky and Herrmann also derived one approximate frequency equation based on shell theory (16). This equation is very lengthy, so it is not listed here. Basically, this equation is in following format:

$$F_{\text{shell}}(s, \delta) = A_1(m)(s^2 - M)^2(s^2 - k^2)^2\delta^8 + [A_2(m)s^6 + A_3(m)s^4 + A_4(m)s^2 + A_5(m)]\delta^6 \\ + [A_6(m)s^4 + A_7(m)s^2 + A_8(m)]\delta^4 - A_9(m)[s^2 - A_{10}(m)]\delta^2 = 0. \quad (3)$$

where $s = c/c_s$, $\delta = h/\Lambda$, A_1, \dots, A_{10} and M are constants which are functions of tube geometry parameter $m = h/R$ (16), ν is the material Poisson's ratio, k is the shear coefficient in M-H shell model which is related to Poisson's ratio ν (15). Here $R = (a + b)/2$ is the mean tube radius. From equation 3, it can be seen that phase speed is a function of both m and δ .

Equation 1 is transcendental in nature but can be solved with the help of mathematical software such as MAPLE or MATHEMATICA. From equation 2, it can be seen that β and/or γ could become imaginary. When $c < c_s$ and $c < c_c$, both β and γ are imaginary. When $c_s < c < c_c$, γ is real but β is imaginary. Wherever one variable becomes imaginary, Bessel function I_m, K_m must be used in place of J_m, Y_m . Such replacement guarantees that the imaginary number i will be eliminated from the equation so that the real roots can be obtained.

Equation 3 can be solved easily using the Newton-Raphson method. There are four real solutions. When the wavelength is very long, δ approaches zero and the first and second solutions of s approach the shear coefficient k . This coefficient k leads numerically to the same phase speed as the limiting solution for wave speed in cylindrical rods when the wavelength approaches infinity. So it is interesting to see that M-H shell model explains the physical meaning of this limiting solution.

The solutions of equations 1, 2, and 3 for various tube geometries are shown in figure 2. There are infinite solutions for the frequency equations. Here, only the first-mode solutions are shown. The following material constants are assumed: $E = 206.09$ GPa, $\rho = 7850$ kg/m³, and Poisson's ratio $\nu = 0.30$. It can be seen that the two models provide very close solutions. The maximum difference occurs at the "valley" of the curves. As an example, for $m = 0.250$, 3-D

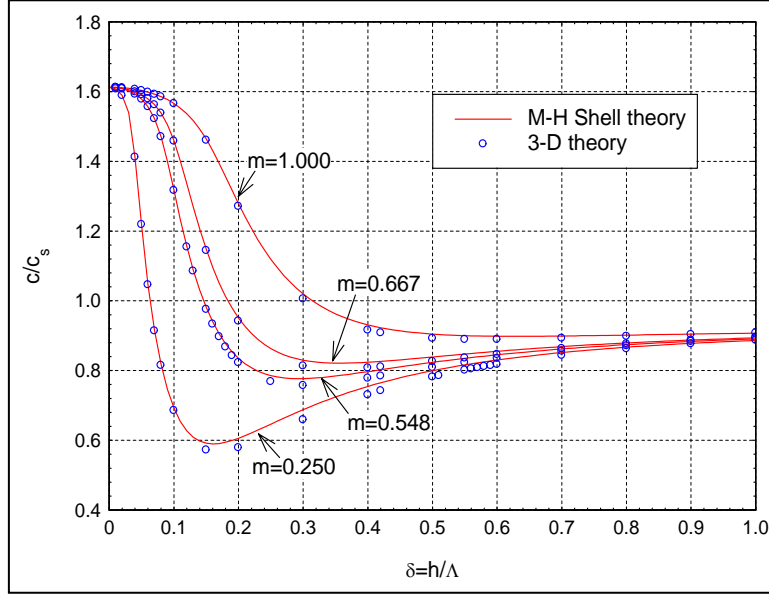


Figure 2. Solution of the frequency by 3-D theory and shell theory for various m values.

theory gives $c/c_s = 0.5720$, shell theory gives $c/c_s = 0.5916$, and the error is $\sim 3\%$. This error is 0.54%, 0.29%, 0.21% for $m = 0.548$, $m = 0.667$ ($2/3$) and $m = 1.000$, respectively. The error decreases when m increases. Figure 3 shows the solutions by shell theory for various m values. When $m = 0.033$ ($1/30$), the phase speed decreases very quickly over the range of low δ . With increasing m , the phase speed drops more slowly with δ . There exists one minimum (valley) point for all the curves, after which speed starts to increase. It is obvious that all the curves approach to one limiting speed when δ goes to infinity. For the material properties used here, this limiting phase speed is $0.927 c_s$.

One important observation from phase speed solutions is that the general claim “wave components with lower frequencies travel faster than wave components with higher frequencies,” which is always true for the cylindrical rod, does not always hold true for the cylindrical tubes. For small m values, the phase speed first drops then increases. When m becomes higher, the claim may hold for the whole range of δ .

On the other hand, in this study, it will be shown that the phase speed will not fall into the range where phase speed increases with δ . When we discuss the results later, for simplicity, we still use the claim that the lower frequency wave moves faster.

Bancroft (6) solved the frequency equation for the cylindrical rod. He gave the value of c_k/c_c when δ approaches infinity. Herrmann and Mirsky (15) also gave these values. The comparison is shown in figure 4. It is clear that these two sets of solutions are exactly the same, which also verifies the correctness of M-H models.

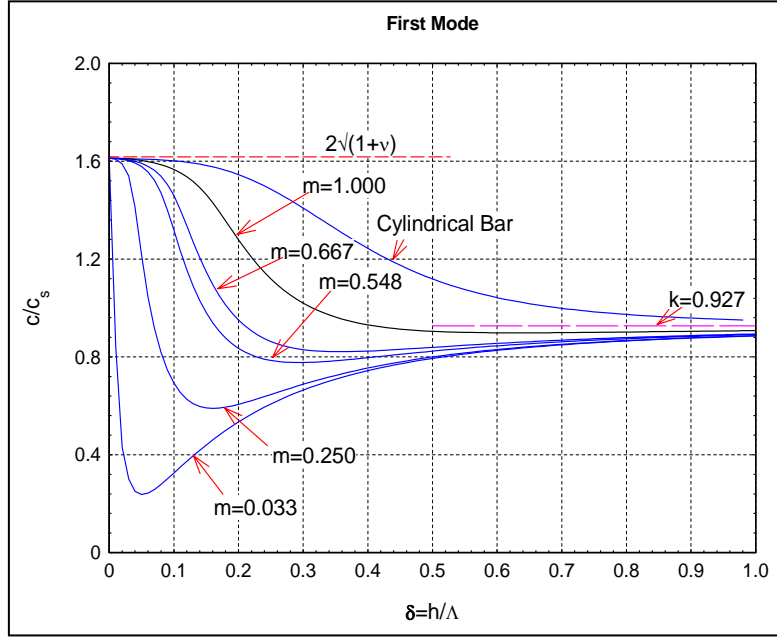


Figure 3. Solution of the frequency equation by shell theory for various $m = h/R$.

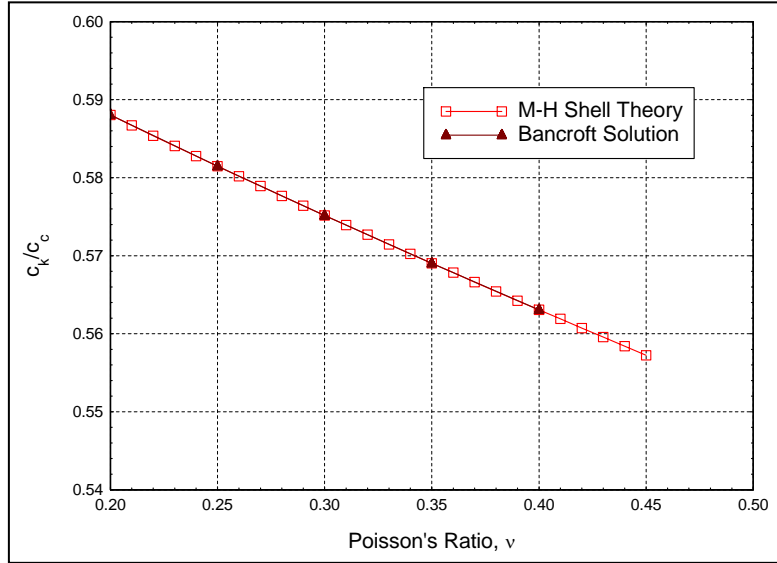


Figure 4. c_k/c_c when $\delta = h/\Lambda$ approaches infinity, $c_c = \sqrt{E/\rho}$.

Now it is proven that the 3-D theory and the shell theory give solutions that can be considered the same. Shell theory solutions will be used for further investigation. The advantage of using the shell theory model is that the frequency equation of the shell model is not transcendental, so it is straightforward to include the model into a computer code.

Mirsky and Herrmann discussed the first-mode solution thoroughly. But they were not sure if wave motion in tubes always follows the first-mode solution, and they did not mention the

application of their models to the SHPB experiment either. So it is not clear if the first-mode solution can be used to determine the phase speed in the SHPB experiments. Follansbee et al. (7) proved that the solid cylindrical bars in the SHPB experiment vibrate in the first mode, so it may also be true for the hollow cylindrical tubes. To prove this assumption, 3-D finite element analysis is performed to simulate the wave motion in the tubes and is compared with the shell theory for the first mode.

3. Modification of Traditional Dispersion Algorithm

3.1 Solution of Phase Speed

In predicting the dispersed waveform by M-H shell model, the first step is to determine the phase speed of every harmonic wave component. Another equation is required in addition to the $c/c_s \sim h/\Lambda$ relationship shown in figure 3:

$$2\pi(c/c_s) \cdot (h/\Lambda) = k\omega_0(h/c_s), \quad (4)$$

which is equivalent to

$$c(k) = f(k) \Lambda = (k\omega_0 / 2\pi) \cdot \Lambda. \quad (5)$$

Here, $k = 1, \dots, K = N/2$ and N are the numbers of strain data collected by the strain gages. Phase speed $c(k)$ can be solved by finding the intersection of the two curves represented by equations 3–5 numerically. Felice (17) performed nonlinear fitting on the solution of frequency equation for cylindrical rods to obtain one explicit relationship between c/c_s and h/Λ . Then it was easy to use this relationship and equation 4–5 together to determine the phase speed. For cylindrical tubes, this fitting method does not work because the shape of the $c/c_s \sim h/\Lambda$ curves changes significantly with m as shown in figure 3. On the other hand, the nonlinear fitting is not necessary. This is because there is one implicit functional relationship between c/c_s and h/Λ in equation 3. Giving one h/Λ value, the first-mode solution c/c_s can be determined numerically from equation 3. With the help of this observation, the phase speed of wave components can be determined using equations 3 and 4.

3.2 Reconstruction of Waveform

A modification is suggested in this study on dispersion correction. In traditional dispersion correction algorithm, the following equation is used to reconstruct the waveform:

$$f(t) = \frac{A_0}{2} + \sum_{k=1}^{N/2} [A_k \cos(k\omega_0 t') + B_k \sin(k\omega_0 t')], \quad (6)$$

with

$$t' = t - \Delta z \left(\frac{1}{c_k} - \frac{1}{c_0} \right). \quad (7)$$

Here, A_0, A_k , and B_k are the coefficients of harmonic wave components determined by Fourier transform (FT). Δz is the distance between the strain gage and the destination position. c_k is the phase speed of the wave with frequency $k\omega_0$. This modification is explained in figure 5. Suppose there are two sinusoidal waves $\sin(t)$ and $\sin(2t)$ traveling together in a tube. At location A, the two waves are in phase. Now let them travel forward to location B. Because the wave with higher frequency travels slower than the wave with lower frequency, wave $\sin(t)$ will arrive at location B earlier (at time T_1) than $\sin(2t)$ (at time T_2). From time T_1 to time T_2 , the contribution from wave $\sin(2t)$ to stress and strain at location B should be zero because it has not arrived yet. In the traditional algorithm, the stress and strain response is taken to be $\sin(2(t - L_{AB}/c_2 + L_{AB}/c_0))$, where L_{AB} is the distance between location A and location B, c_2 is the phase speed for $\sin(2t)$, and c_0 is the fundamental speed.

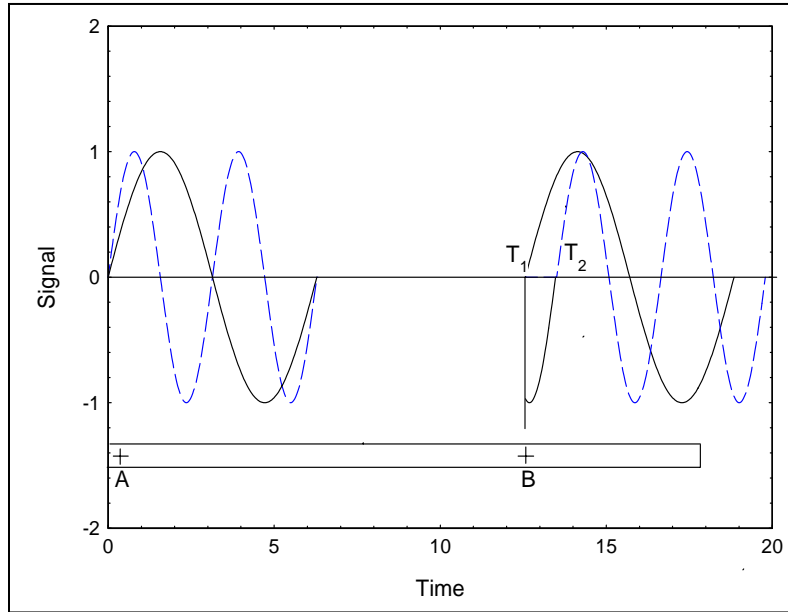


Figure 5. Explanation of new dispersion algorithm for SHPB.

Based on this observation, the algorithm for inverse fast Fourier transform (FFT) in SHPB application should be modified. Suppose the initial time the signal arrives at one certain position is $t = 0$. At time $t = t_x$, the signal should be reconstructed as in the following pseudocode:

Signal: = $A_0/2.0$;

For $k=1$ to $N/2$

If ($t_x < (\Delta z / c_k - \Delta z / c_0)$)

Do nothing;

Else

$$\text{Signal} \leftarrow \text{Signal} + A_k \cos(k\omega_0(tx - \Delta z/c_k + \Delta z/c_0)) + B_k \sin(k\omega_0(tx - \Delta z/c_k + \Delta z/c_0));$$

The higher frequency wave travels slower than the lower frequency wave. The lower frequency wave reaches location B at time T_1 . No response should be generated by the higher frequency wave at location B until after time T_2 .

After the coefficients A_0 , A_k , and B_k are determined, this modified dispersion algorithm is applied to each harmonic component in reconstructing the waveform.

4. Finite Element (FE) Analysis

FE analysis was performed to check the prediction of the M-H shell model. Stress wave propagation in two cylindrical tubes was simulated. These tubes have $m = h/R$ values of 0.548–0.667. The dimensions of the tube with $m = 0.548$ are as follows: inner radius $a = 7.24$ mm, outer radius $b = 12.7$ mm, and the length is $L = 1.524$ m. Tubes with such dimensions are commercially available and suitable for Hopkinson bar applications. The dimensions of the tube with $m = 0.667$ are as follows: inner radius $a = 5.46$ mm, outer radius $b = 10.92$ mm, and the length is $L = 1.524$ m. Both tubes have a wall thickness of 5.46 mm. The tube material is modeled as steel with Young's modulus $E = 206.09$ GPa, Poisson's ratio $\nu = 0.3$, and density $\rho = 7850$ Kg/m³. A trapezoidal stress pulse is applied at one end of the tube, and the wave propagation in the tube is monitored. The other end is assumed to be traction free, so the stress wave will reflect from that end. Due to the symmetric nature of this problem, only one quarter of the tube is analyzed.

Commercial FE analysis code ABAQUS/Explicit* was used to perform the analysis. Element type C3D8R, which is 8-node brick element with reduced integration, was used to generate the mesh. The numbers of elements along the radial direction, tangential direction, and axial direction are 5, 20, and 600, respectively, with a total of 60,000 elements. These elements are uniformly distributed along the axial direction. Figure 6 shows the model and the mesh generation. The boundary conditions are set as follows: zero x displacement along edge $X = 0$; and zero y displacement along edge $Y = 0$. Figure 7 defines the trapezoidal stress pulse applied on the end face $Z = 0$. The stress history is defined with several time and stress parameters as described in figure 7. The values used in the present analyses are as follows: $t_A = 0$ μ s, $t_B = 25$ μ s, $t_C = 35$ μ s, $t_D = 105$ μ s, $t_E = 115$ μ s, $t_F = 140$ μ s and $P_{\max} = 500$ MPa.

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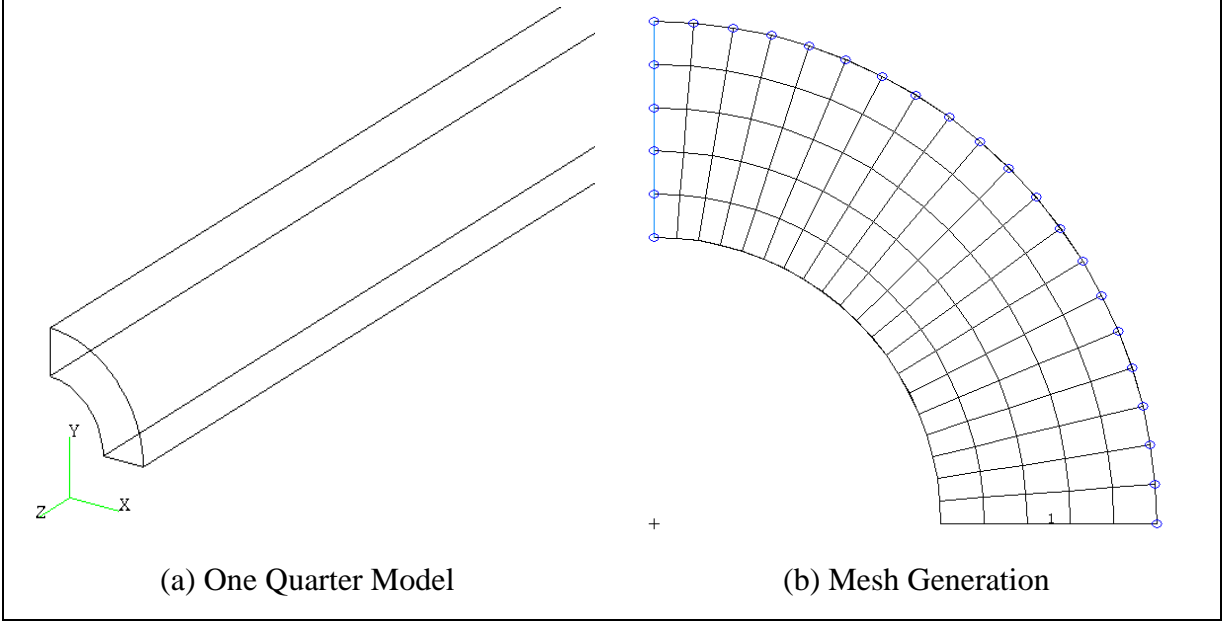


Figure 6. FE model of a cylindrical tube.

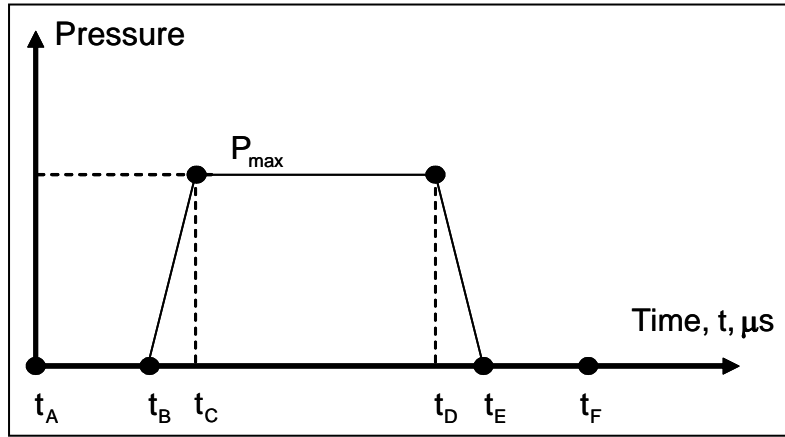


Figure 7. Definition of stress wave applied on the end surface of the cylindrical tube.

Figure 8 gives the strain history at the mid-length of tube for a time period up to 700 μs . The results of FE analyses are compared with M-H shell theory and are presented in the next section.

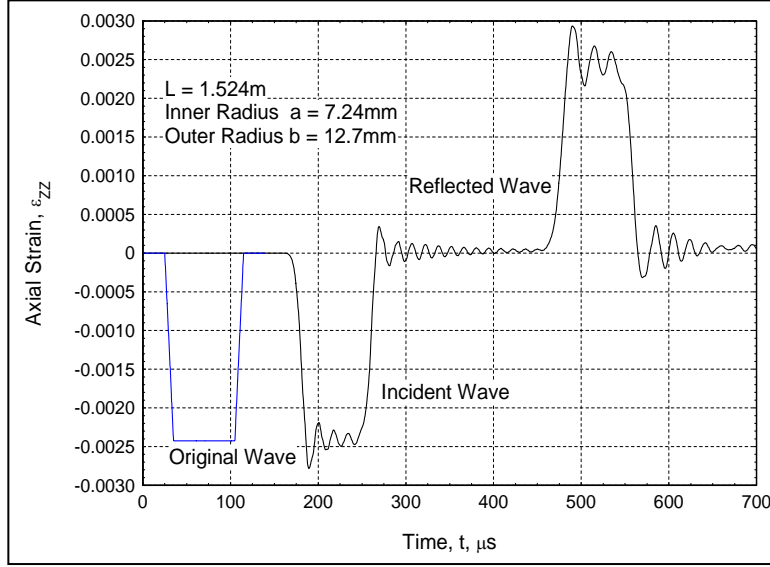


Figure 8. Strain vs. time at the mid-length of the tube.

5. Results and Discussion

The axial strain predictions by both M-H model and FE analysis for the two cylindrical tubes at $z/L = 0.50-0.75$ are presented in figures 9 and 10. When the M-H model is used, an implicit assumption is made that the wave propagation in the tubes is 1-D, and strain is determined from stress by Hooke's law $\varepsilon_{zz} = \sigma_{zz} / E$. Plots in the left column show the complete strain history, and the closer views in the peak region are listed in the right column. From the four plots in figures 9 and 10, it is obvious that the predictions by the M-H model and FEM analysis are very close. The rising parts of the waves are almost overlapping. For the peak part, the Pochhammer modes match very well. The only difference is that for the M-H model, the beginning part of the waves is abnormal, which will be explained later. The results in figures 9 and 10 prove that the cylindrical tubes in the SHPB experiment also vibrate in the first mode.

Figure 11 compares the wave dispersion results by the traditional algorithm, and the new algorithm used in this study. Here the strain data are plotted in the opposite sign. The results by the traditional algorithm are not smooth, and discontinuities are seen over the peak part of the waves. On the contrary, the modified algorithm predicts fairly smooth waveform. From the smooth waves, the number of Pochhammer modes can be clearly counted. If the old algorithm is compared to FE results, it is nearly impossible to reach the conclusion that wave motion in tubes follows the first-mode solution of M-H model. The comparison clearly verifies the correctness and necessity of the new algorithm.

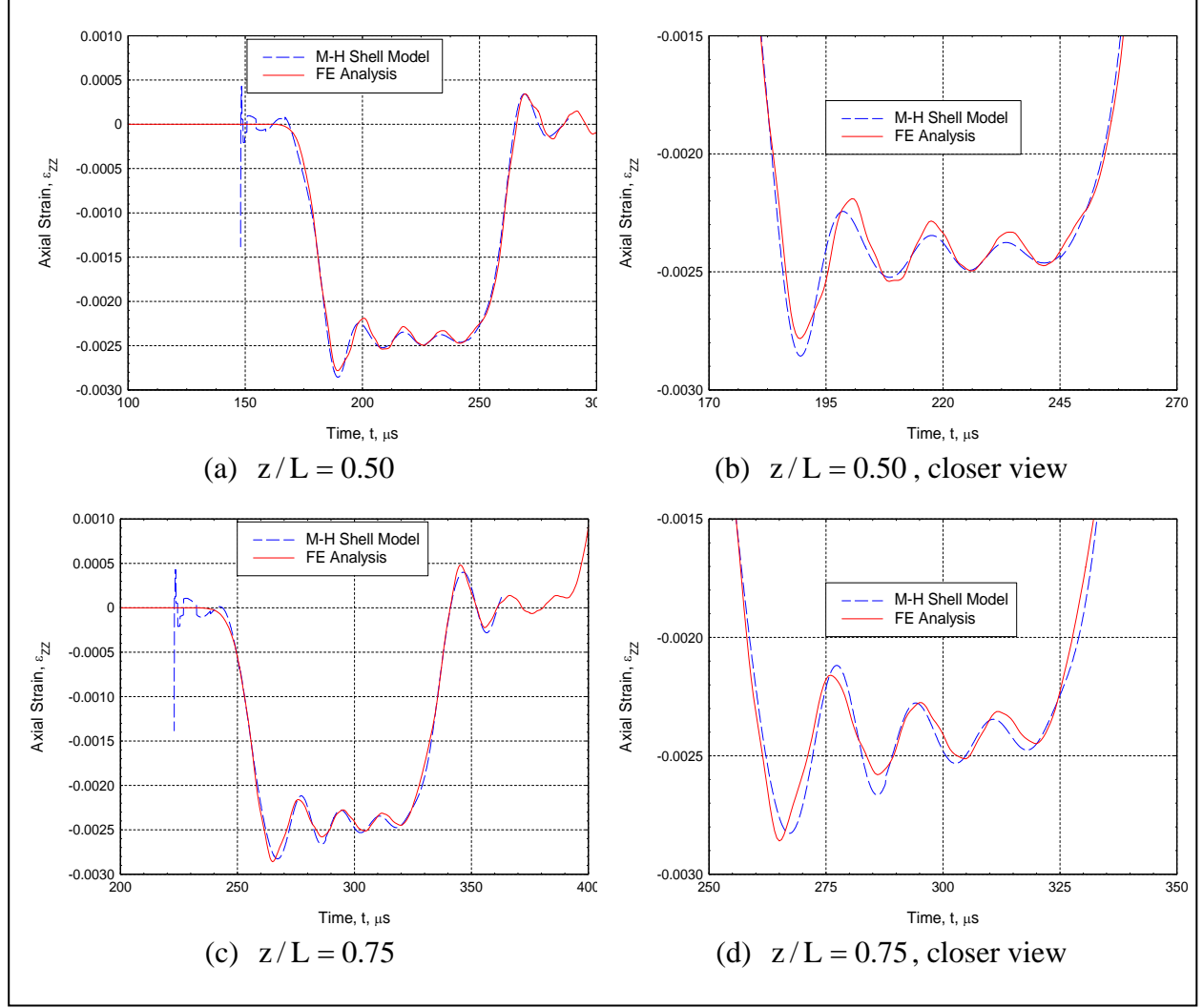


Figure 9. Axial strain predicted by M-H model and FE analysis for the tube with $m = 0.548$.

But why does the traditional algorithm work for rods? Figure 12 gives an example for the use of both algorithms on the rod with $\nu = 0.29$. It is seen that the predicted wave by traditional algorithm still has some discontinuous response in the later part of the wave peak, although the difference between the two algorithms is not as significant as for the tubes. From figure 3, it can be seen that the phase speed in rods changes very slowly with δ , compared with phase speed in tubes. This leads to more Pochhammer modes for rods than the tubes. Because the irregularities occur at the later part of the wave peak, the traditional algorithm still gives wave dispersion prediction accurate enough for engineering application, and the shortcoming of the traditional algorithm is concealed. In this study of wave dispersion in tubes, the limitation of the traditional wave dispersion algorithm is identified first.

The first part of the wave dispersion prediction by the new algorithm shows abnormal behavior. This is because at the beginning, relatively few wave components contribute to the dispersed wave, which can be seen from the algorithm described earlier. The M-H model assumes infinite

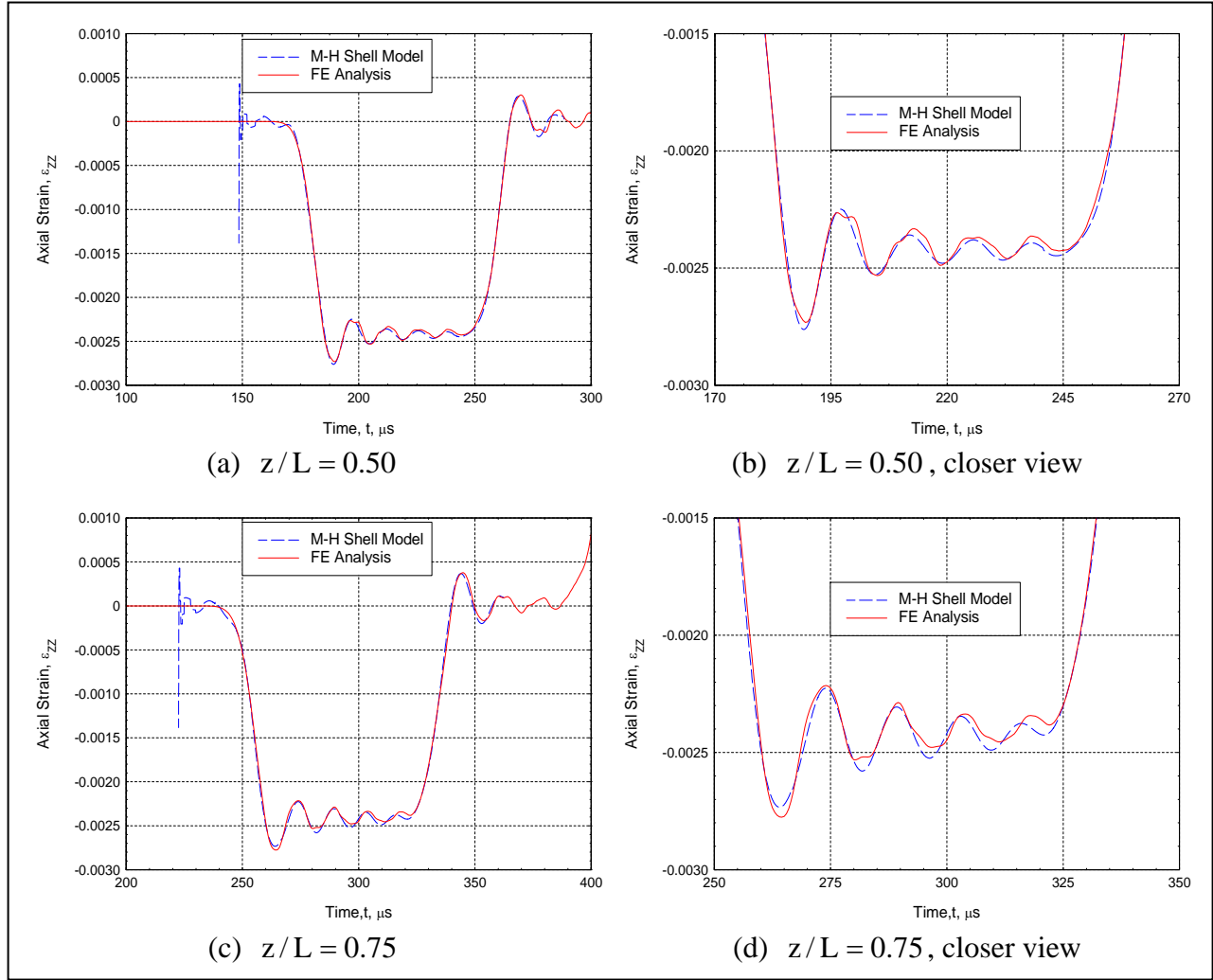


Figure 10. Axial strain predicted by M-H model and FE analysis for the tube with $m = 0.667$.

long tubes and continuous wave components. Under these assumptions, at any instance, all the wave components contribute to the whole waveform, so this abnormal behavior will not be seen. This phenomenon cannot be seen in real tests or in an FEM simulation either. When the new algorithm is used to predict the dispersed wave, it is assumed that the wave has period of 1400 μs during which the FT is performed. This input wave is a pulse wave rather than a continuous wave. The new algorithm does not allow any summation of wave components if the travel time condition is not satisfied. Thus the initial data are spurious till all the wave components have arrived at the particular point of interest. This problem can be resolved by taking a wider time window during FT and reducing the window during reconstruction.

When rods are used in the SHPB test, the only geometric parameter affecting the wave propagation in rods is the radius. If tubes are used in the SHPB test, two more parameters are involved: the inner radius and the m value. Among the outer radius, inner radius, tube wall

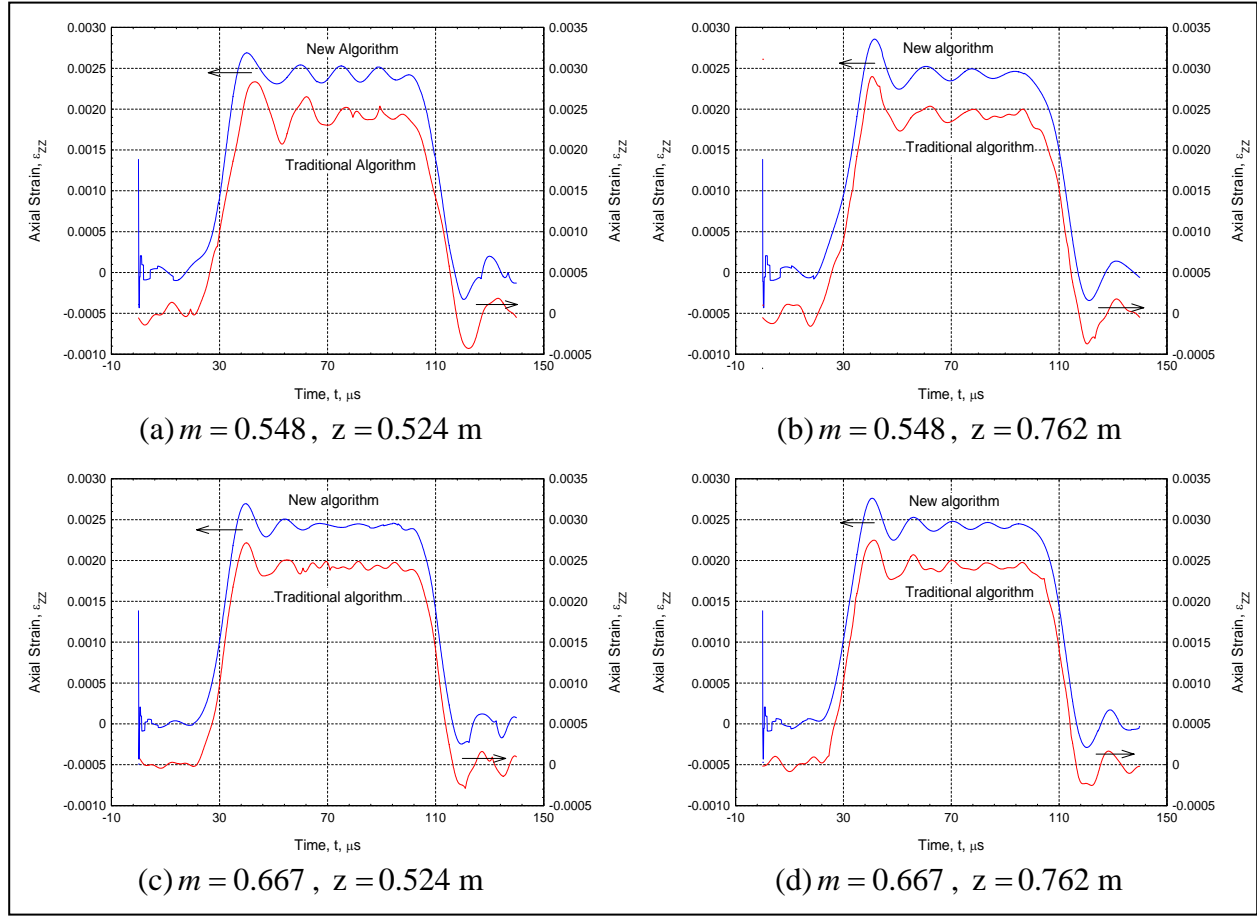


Figure 11. Comparison of new and traditional dispersion algorithms.

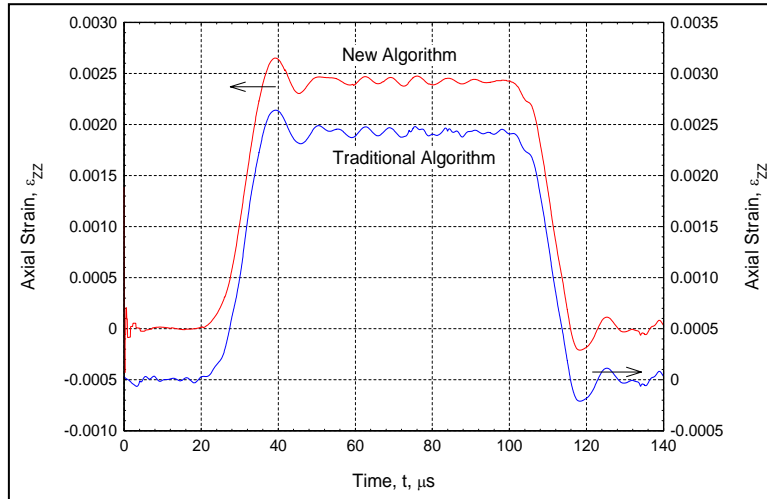


Figure 12. Dispersed wave in rod determined by the new algorithm and traditional algorithm. Material Poisson's ratio = 0.29.

thickness h and m , only two are independent. The discussion below will focus on h and m . It can be seen from figure 3 that when m takes lower values, the phase speed decreases more quickly when δ is small. For a fixed m value, when the tube wall is thinner, the phase speed for all the wave components will be closer than when the h value is higher. This can be seen graphically from figure 3. So lower m values and higher h values will make the phase speed decreases faster as a function of frequency, which will make the wave become wider and wider when it propagates in the tube. To catch all the wave components, a wider time window must be used to process the strain data. Usually a computer code is used to automatically select the processing window. For example, Leber's method (18) finds the processing window in the following way: first find a window between the point where the wave rises and the point where the wave drops to zero again. Another window that is ~33% wider than the first window and includes the first window in the middle is used as the processing window. If the wave becomes too wide, an incorrect window may be chosen which omits some important components. Furthermore, the incident wave, and the reflected wave will not contain the same amount of information because the reflected wave is wider than the incident wave, but the processing windows are still the same width. To obtain an accurate result, it is recommended to use a tube with higher m value and lower h value. Such a combination is actually not difficult to realize.

When tubes are used in the SHPB technique, several configurations of the apparatus are possible. If an incident tube and a transmission tube are used as the apparatus, it is recommended that one hollow cylindrical specimen be used. This requires that the tubes and the specimen have the same inner and outer diameters. The advantage of this configuration is that the 1-D requirement of the SHPB technique can be better satisfied than using rods. Figure 13 shows the stress history at the integration point of all the five elements at $z = 1.00$ m along the radial direction. It is seen that for all five elements, the axial stress history σ_{zz} vs. time is nearly the same. The normal stresses in the other two directions are also plotted. Figure 13 also shows that the stress σ_{xx} is very low (maximum is 13 MPa) compared to σ_{zz} (maximum is 580 MPa), and the stress σ_{yy} is even lower (maximum is 0.7 MPa). So the stress distribution can be considered as 1-D, and the axial stress distribution is uniform across the cross-section of the tube. The strains in x and y directions can be considered only due to Poisson's effect. Another option is described by Chen (12), where only the TT is used. When this configuration is used, a cap must be inserted between specimen and TT to transfer the load. It is not clear what effect this cap might have on the stress wave propagation and will be addressed in a separate work.

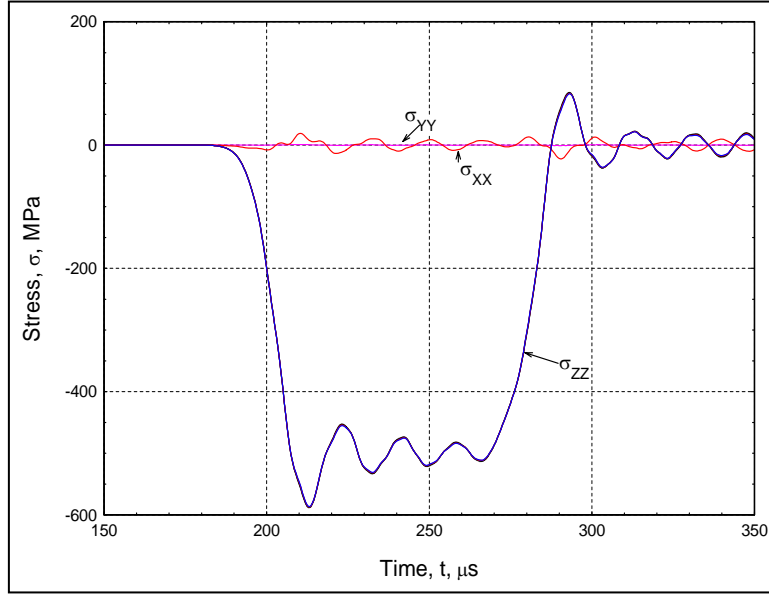


Figure 13. Stress history of all elements at $z = 1.00$ m along $X = 0$ axis.

6. Conclusions

In this report, wave dispersion in cylindrical tubes applied to the SHPB experiments is studied. The main conclusions are as follows:

1. The M-H shell model gives the same result as the 3-D model.
2. The FE study shows that wave propagation in tubes follows the first-mode solution of the M-H shell model.
3. A new dispersion algorithm is suggested, and it can better predict the dispersion wave.
4. For purpose of the SHPB application, tubes with higher m and lower h values should be used.

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1 ARMTEC DEFENSE PRODUCTS
S DYER
85 901 AVE 53
PO BOX 848
COACHELLA CA 92236

1 NATL COMPOSITE CTR
T CORDELL
2000 COMPOSITE DR
KETTERING OH 45420

3 PACIFIC NORTHWEST LAB
M SMITH
G VAN ARSDALE
R SHIPPELL
PO BOX 999
RICHLAND WA 99352

1 SAIC
M PALMER
1410 SPRING HILL RD STE 400
MS SH4 5
MCLEAN VA 22102

NO. OF
COPIES ORGANIZATION

1 ALLIANT TECHSYSTEMS INC
4700 NATHAN LN N
PLYMOUTH MN 55442-2512

1 APPLIED COMPOSITES
W GRISCH
333 NORTH SIXTH ST
ST CHARLES IL 60174

1 CUSTOM ANALYTICAL
ENG SYS INC
A ALEXANDER
13000 TENSOR LANE NE
FLINTSTONE MD 21530

1 AAI CORP
DR N B MCNELLIS
PO BOX 126
HUNT VALLEY MD 21030-0126

1 OFC DEPUTY UNDER SEC DEFNS
J THOMPSON
1745 JEFFERSON DAVIS HWY
CRYSTAL SQ 4 STE 501
ARLINGTON VA 22202

3 ALLIANT TECHSYSTEMS INC
J CONDON
E LYNAM
J GERHARD
WV01 16 STATE RT 956
PO BOX 210
ROCKET CENTER WV
26726-0210

1 PROJECTILE TECHNOLOGY INC
515 GILES ST
HAVRE DE GRACE MD 21078

1 HEXCEL INC
R BOE
PO BOX 18748
SALT LAKE CITY UT 84118

1 PRATT & WHITNEY
C WATSON
400 MAIN ST MS 114 37
EAST HARTFORD CT 06108

NO. OF
COPIES ORGANIZATION

5 NORTHROP GRUMMAN
B IRWIN
K EVANS
D EWART
A SHREKENHAMER
J MCGLYNN
BLDG 160 DEPT 3700
1100 WEST HOLLYVALE ST
AZUSA CA 91701

1 HERCULES INC
HERCULES PLAZA
WILMINGTON DE 19894

1 BRIGS COMPANY
J BACKOFEN
2668 PETERBOROUGH ST
HERNDON VA 22071-2443

1 ZERNOW TECHNICAL SERVICES
L ZERNOW
425 W BONITA AVE STE 208
SAN DIMAS CA 91773

1 GENERAL DYNAMICS OTS
L WHITMORE
10101 NINTH ST NORTH
ST PETERSBURG FL 33702

2 GENERAL DYNAMICS OTS
FLINCHBAUGH DIV
K LINDE
T LYNCH
PO BOX 127
RED LION PA 17356

1 GKN WESTLAND AEROSPACE
D OLDS
450 MURDOCK AVE
MERIDEN CT 06450-8324

2 BOEING ROTORCRAFT
P MINGURT
P HANDEL
800 B PUTNAM BLVD
WALLINGFORD PA 19086

NO. OF
COPIES ORGANIZATION

5 SIKORSKY AIRCRAFT
G JACARUSO
T CARSTENSAN
B KAY
S GARBO MS S330A
J ADELMANN
6900 MAIN ST
PO BOX 9729
STRATFORD CT 06497-9729

1 AEROSPACE CORP
G HAWKINS M4 945
2350 E EL SEGUNDO BLVD
EL SEGUNDO CA 90245

2 CYTEC FIBERITE
M LIN
W WEB
1440 N KRAEMER BLVD
ANAHEIM CA 92806

2 UDLP
G THOMAS
M MACLEAN
PO BOX 58123
SANTA CLARA CA 95052

1 UDLP WARREN OFC
A LEE
31201 CHICAGO RD SOUTH
SUITE B102
WARREN MI 48093

2 UDLP
R BRYNSVOLD
P JANKE MS 170
4800 EAST RIVER RD
MINNEAPOLIS MN 55421-1498

1 LOCKHEED MARTIN
SKUNK WORKS
D FORTNEY
1011 LOCKHEED WAY
PALMDALE CA 93599-2502

1 LOCKHEED MARTIN
R FIELDS
5537 PGA BLVD
SUITE 4516
ORLANDO FL 32839

NO. OF
COPIES ORGANIZATION

1 NORTHROP GRUMMAN CORP
ELECTRONIC SENSORS
& SYSTEMS DIV
E SCHOCH MS V 16
1745A W NURSERY RD
LINTHICUM MD 21090

1 GDLS DIVISION
D BARTLE
PO BOX 1901
WARREN MI 48090

2 GDLS
D REES
M PASIK
PO BOX 2074
WARREN MI 48090-2074

1 GDLS
MUSKEGON OPER
M SOIMAR
76 GETTY ST
MUSKEGON MI 49442

1 GENERAL DYNAMICS
AMPHIBIOUS SYS
SURVIVABILITY LEAD
G WALKER
991 ANNAPOLIS WAY
WOODBIDGE VA 22191

6 INST FOR ADVANCED
TECH
H FAIR
I MCNAB
P SULLIVAN
S BLESS
W REINECKE
C PERSAD
3925 W BRAKER LN STE 400
AUSTIN TX 78759-5316

1 ARROW TECH ASSOC
1233 SHELBURNE RD STE D8
SOUTH BURLINGTON VT
05403-7700

1 R EICHELBERGER
CONSULTANT
409 W CATHERINE ST
BEL AIR MD 21014-3613

NO. OF
COPIES ORGANIZATION

1 SAIC
G CHRYSSOMALLIS
8500 NORMANDALE LAKE BLVD
SUITE 1610
BLOOMINGTON MN 55437-3828

1 UCLA MANE DEPT ENGR IV
H T HAHN
LOS ANGELES CA 90024-1597

2 UNIV OF DAYTON
RESEARCH INST
R Y KIM
A K ROY
300 COLLEGE PARK AVE
DAYTON OH 45469-0168

1 UMASS LOWELL
PLASTICS DEPT
N SCHOTT
1 UNIVERSITY AVE
LOWELL MA 01854

1 IIT RESEARCH CTR
D ROSE
201 MILL ST
ROME NY 13440-6916

1 GA TECH RESEARCH INST
GA INST OF TCHNLGY
P FRIEDERICH
ATLANTA GA 30392

1 MICHIGAN ST UNIV
MSM DEPT
R AVERILL
3515 EB
EAST LANSING MI 48824-1226

1 UNIV OF WYOMING
D ADAMS
PO BOX 3295
LARAMIE WY 82071

1 PENN STATE UNIV
R S ENGEL
245 HAMMOND BLDG
UNIVERSITY PARK PA 16801

NO. OF
COPIES ORGANIZATION

2 PENN STATE UNIV
R MCNITT
C BAKIS
212 EARTH ENGR
SCIENCES BLDG
UNIVERSITY PARK PA 16802

1 PURDUE UNIV
SCHOOL OF AERO & ASTRO
C T SUN
W LAFAYETTE IN 47907-1282

1 STANFORD UNIV
DEPT OF AERONAUTICS
& AEROBALLISTICS
S TSAI
DURANT BLDG
STANFORD CA 94305

1 UNIV OF MAINE
ADV STR & COMP LAB
R LOPEZ ANIDO
5793 AEWB BLDG
ORONO ME 04469-5793

1 JOHNS HOPKINS UNIV
APPLIED PHYSICS LAB
P WIENHOLD
11100 JOHNS HOPKINS RD
LAUREL MD 20723-6099

1 UNIV OF DAYTON
J M WHITNEY
COLLEGE PARK AVE
DAYTON OH 45469-0240

1 NORTH CAROLINA ST UNIV
CIVIL ENGINEERING DEPT
W RASDORF
PO BOX 7908
RALEIGH NC 27696-7908

5 UNIV OF DELAWARE
CTR FOR COMPOSITE MTRLS
J GILLESPIE
M SANTARE
S YARLAGADDA
S ADVANI
D HEIDER
201 SPENCER LAB
NEWARK DE 19716

NO. OF
COPIES ORGANIZATION

1 DEPT OF MTRL
SCIENCE & ENGRG
UNIV OF ILLINOIS
AT URBANA CHAMPAIGN
JECONOMY
1304 WEST GREEN ST 115B
URBANA IL 61801

1 UNIV OF MARYLAND
DEPT OF AEROSPACE ENGRG
A J VIZZINI
COLLEGE PARK MD 20742

1 DREXEL UNIV
A S D WANG
3141 CHESTNUT ST
PHILADELPHIA PA 19104

3 UNIV OF TEXAS AT AUSTIN
CTR FOR ELECTROMECHANICS
J PRICE
A WALLS
J KITZMILLER
10100 BURNET RD
AUSTIN TX 78758-4497

3 VA POLYTECHNICAL
INST & STATE UNIV
DEPT OF ESM
M W HYER
K REIFSNIDER
R JONES
BLACKSBURG VA 24061-0219

1 SOUTHWEST RESEARCH INST
ENGR & MATL SCIENCES DIV
J RIEGEL
6220 CULEBRA RD
PO DRAWER 28510
SAN ANTONIO TX 78228-0510

1 BATELLE NATICK OPERS
B HALPIN
313 SPEEN ST
NATICK MA 01760

3 DIRECTOR
US ARMY RESEARCH LAB
AMSRD ARL WM MB
A FRYDMAN
2800 POWDER MILL RD
ADELPHI MD 20783-1197

NO. OF
COPIES ORGANIZATION

ABERDEEN PROVING GROUND

1 US ARMY ATC
CSTE DTC AT AC I
W C FRAZER
400 COLLERAN RD
APG MD 21005-5059

91 DIR USARL
AMSRD ARL CI
AMSRD ARL O AP EG
M ADAMSON
AMSRD ARL SL BA
AMSRD ARL SL BB
D BELY
AMSRD ARL WM
J SMITH
H WALLACE
AMSRD ARL WM B
A HORST
T KOGLER
AMSRD ARL WM BA
D LYON
AMSRD ARL WM BC
J NEWILL
P PLOSTINS
A ZIELINSKI
AMSRD ARL WM BD
P CONROY
B FORCH
M LEADORE
C LEVERITT
R LIEB
R PESCE RODRIGUEZ
B RICE
AMSRD ARL WM BF
S WILKERSON
AMSRD ARL WM M
B FINK
J MCCAULEY
AMSRD ARL WM MA
L GHIORSE
S MCKNIGHT
E WETZEL
AMSRD ARL WM MB
J BENDER
T BOGETTI
L BURTON
R CARTER
K CHO
W DE ROSSET
G DEWING
R DOWDING
W DRYSDALE

NO. OF
COPIES ORGANIZATION

R EMERSON
D HENRY
D HOPKINS
R KASTE
L KECSKES
M MINNICINO
B POWERS
D SNOHA
J SOUTH
M STAKER
J SWAB
J TZENG
AMSRD ARL WM MC
J BEATTY
R BOSSOLI
E CHIN
S CORNELISON
D GRANVILLE
B HART
J LASALVIA
J MONTGOMERY
F PIERCE
E RIGAS
W SPURGEON
AMSRD ARL WM MD
B CHEESEMAN
P DEHMER
R DOOLEY
G GAZONAS
S GHIORSE
C HOPPEL
M KLUSEWITZ
W ROY
J SANDS
D SPAGNUOLO
S WALSH
S WOLF
AMSRD ARL WM RP
J BORNSTEIN
C SHOEMAKER
AMSRD ARL WM T
B BURNS
AMSRD ARL WM TA
W BRUCHEY
M BURKINS
W GILLICH
B GOOCH
T HAVEL
E HORWATH
M NORMANDIA
J RUNYEON
M ZOLTOSKI

NO. OF
COPIES ORGANIZATION

AMSRD ARL WM TB
P BAKER
AMSRD ARL WM TC
R COATES
AMSRD ARL WM TD
D DANDEKAR
T HADUCH
T MOYNIHAN
M RAFTENBERG
S SCHOENFELD
T WEERASOORIYA
AMSRD ARL WM TE
A NILER
J POWELL

NO. OF
COPIES ORGANIZATION

1 LTD
R MARTIN
MERL
TAMWORTH RD
HERTFORD SG13 7DG
UK

1 SMC SCOTLAND
P W LAY
DERA ROSYTH
ROSYTH ROYAL DOCKYARD
DUNFERMLINE FIFE KY 11 2XR
UK

1 CIVIL AVIATION
ADMINSTRATION
T GOTTESMAN
PO BOX 8
BEN GURION INTRNL AIRPORT
LOD 70150
ISRAEL

1 AEROSPATIALE
S ANDRE
A BTE CC RTE MD132
316 ROUTE DE BAYONNE
TOULOUSE 31060
FRANCE

1 DRA FORT HALSTEAD
P N JONES
SEVEN OAKS KENT TN 147BP
UK

1 SWISS FEDERAL ARMAMENTS
WKS
W LANZ
ALLMENDSTRASSE 86
3602 THUN
SWITZERLAND

1 DYNAMEC RESEARCH LAB
AKE PERSSON
BOX 201
SE 151 23 SODERTALJE
SWEDEN

NO. OF
COPIES ORGANIZATION

1 ISRAEL INST OF TECHLGY
S BODNER
FACULTY OF MECHANICAL
ENGR
HAIFA 3200
ISRAEL

1 DSTO
WEAPONS SYSTEMS DIVISION
N BURMAN RLLWS
SALISBURY
SOUTH AUSTRALIA 5108
AUSTRALIA

1 DEF RES ESTABLISHMENT
VALCARTIER
A DUPUIS
2459 BLVD PIE XI NORTH
VALCARTIER QUEBEC
CANADA
PO BOX 8800 COURCELETTE
GOA IRO QUEBEC
CANADA

1 ECOLE POLYTECH
J MANSON
DMX LTC
CH 1015 LAUSANNE
SWITZERLAND

1 TNO DEFENSE RESEARCH
R IJSSELSTEIN
ACCOUNT DIRECTOR
R&D ARMEE
PO BOX 6006
2600 JA DELFT
THE NETHERLANDS

2 FOA NATL DEFENSE RESEARCH
ESTAB
DIR DEPT OF WEAPONS &
PROTECTION
B JANZON
R HOLMLIN
S 172 90 STOCKHOLM
SWEDEN

NO. OF
COPIES ORGANIZATION

- | | |
|---|--|
| 2 | DEFENSE TECH & PROC
AGENCY GROUND
I CREWTHERR
GENERAL HERZOG HAUS
3602 THUN
SWITZERLAND |
| 1 | MINISTRY OF DEFENCE
RAFAEL
ARMAMENT DEVELOPMENT
AUTH
M MAYSELESS
PO BOX 2250
HAIFA 31021
ISRAEL |
| 1 | TNO DEFENSE RESEARCH
I H PASMAN
POSTBUS 6006
2600 JA DELFT
THE NETHERLANDS |
| 1 | B HIRSCH
TACHKEMONY ST 6
NETAMUA 42611
ISRAEL |
| 1 | DEUTSCHE AEROSPACE AG
DYNAMICS SYSTEMS
M HELD
PO BOX 1340
D 86523 SCHROBENHAUSEN
GERMANY |

INTENTIONALLY LEFT BLANK.